CMC Research at NASA Glenn in 2016: Recent Progress and Plans

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for the 40th Annual Conference
on Composites, Materials and Structures
January 25-29, 2016 in Cocoa Beach, FL

NASA Aeronautics: Strategic Thrusts

Safe, Efficient Growth in Global Operations
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft
- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance
- Develop an integrated prototype of a real-time safety monitoring and assurance system

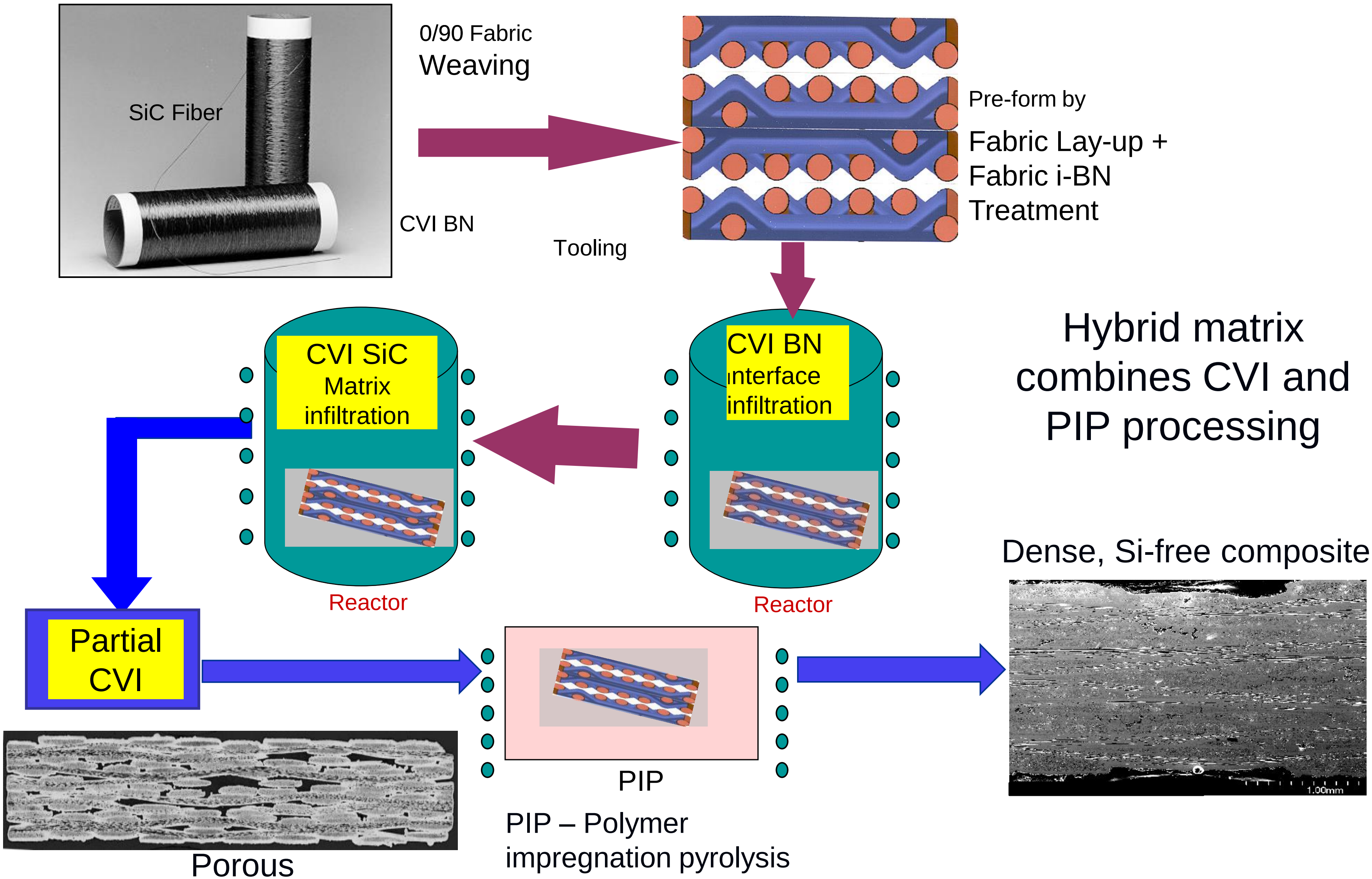
Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications

CMC Research at NASA Glenn

- Material Development & Characterization
- CMC / EBC Durability Modeling & Validation
- Advanced Manufacturing Technologies

CMC Development and Characterization

Hybrid Process for Dense SiC / SiC Composites



2700^{0}F CMC Development and Characterization

Objective: Develop durable 2700^{0}F CMC for turbine components

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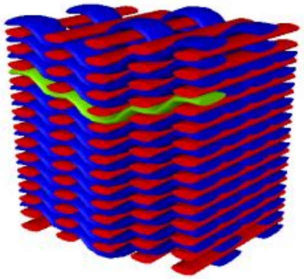
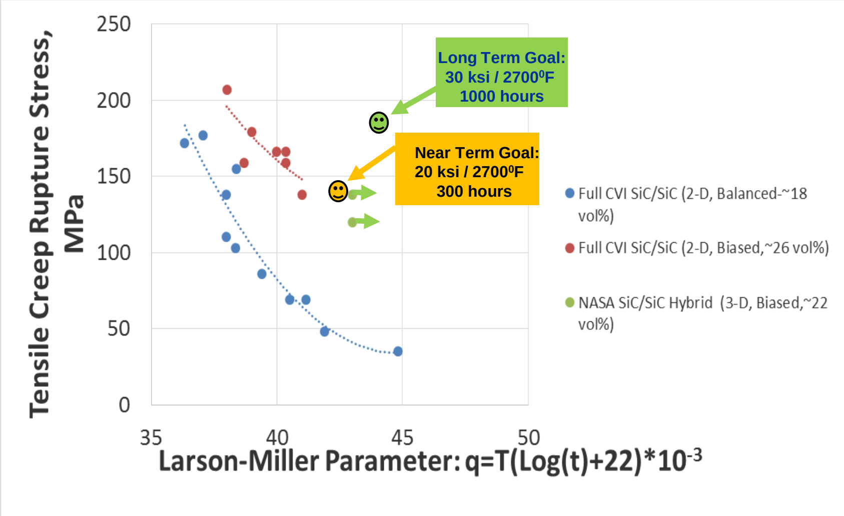
Approach

- Identify optimum constituents and processing methods
- Fabricate 1st generation 2700^{0}F CMC with (CVI+PIP) hybrid matrices and candidate 3D fiber architectures
- Characterize CMC properties and damage mechanisms under static and cyclic conditions for at least 300 hours at 2700^{o}F
- Fabricate 2nd generation 2700^{0}F CMC with optimized fiber architecture and constituents for component applications
- Characterize mechanical properties and damage mechanisms of optimized Gen-2 CMC under static and cyclic conditions.



Modified Angle Interlock fiber architecture



Accomplishments

- Demonstrated 20 ksi / 2700^{0}F / 300 hours durability under creep, fatigue and combined (creep + fatigue) loading for CMC with hybrid matrix and Sylramic-iBN fibers
- Identified optimal fiber architecture (3D Modified Angle Interlock) for Gen-2 CMC with hybrid matrix and Super Sylramic-iBN fibers
- Demonstrated microstructural and cyclic stability of 2700^{o}F EBC on 3D woven SiC/SiC Composites with (CVI+PIP) hybrid matrix at 2700^{o}F for 300 hours

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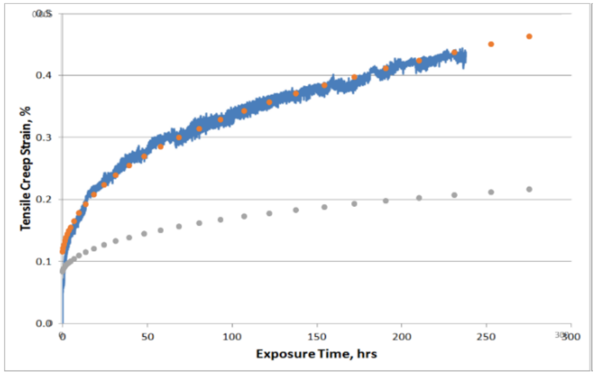
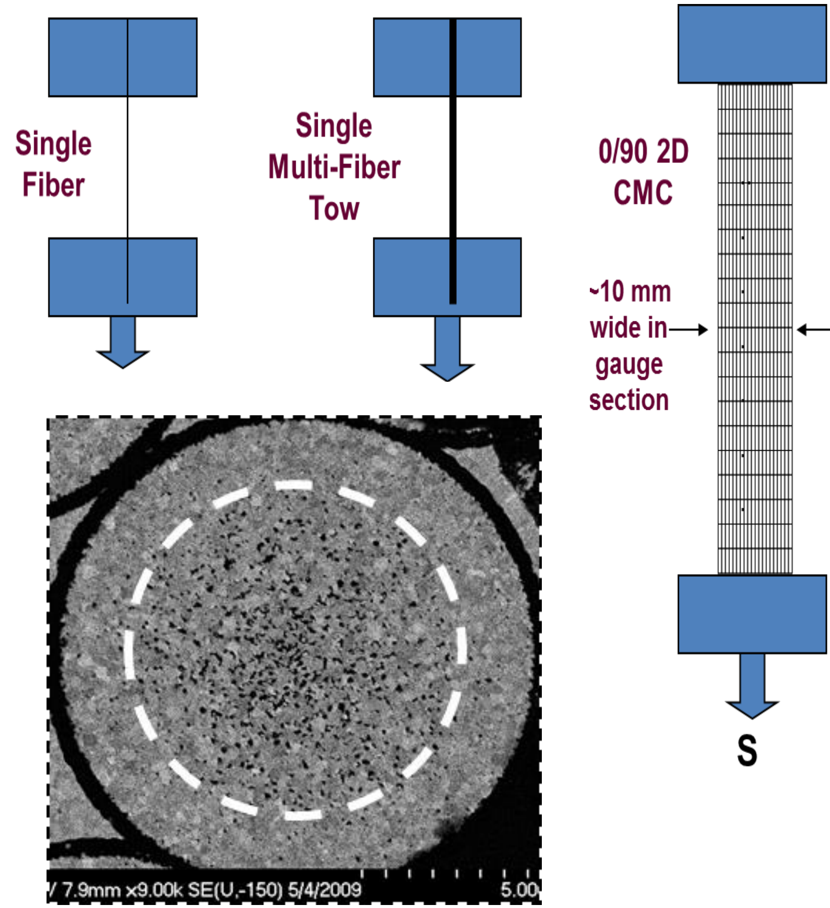
Fiber Research for 2700ºF SiC/SiC CMC

Test and characterize key properties of potential 2700ºF SiC fibers in order to:

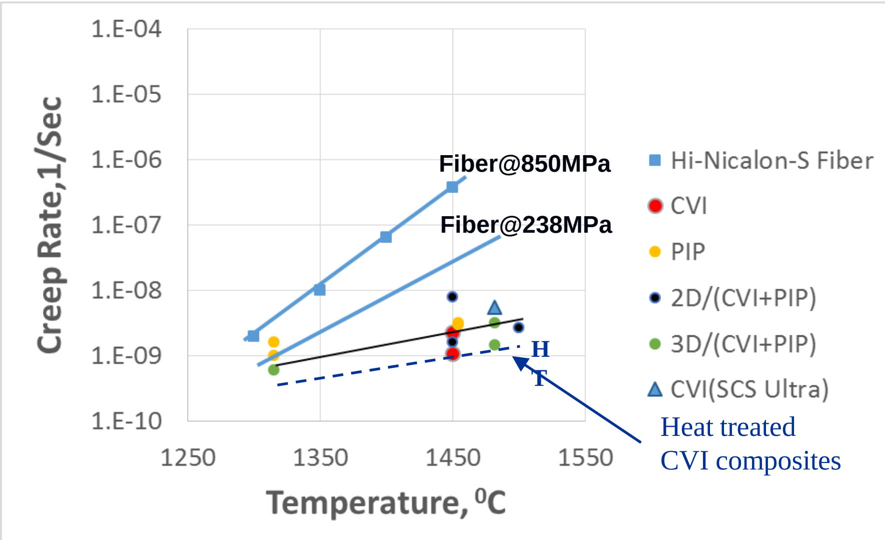
- Understand basic mechanisms
- Develop approaches for property improvement
- Develop analytical fiber and CMC models for time-temperature deformation and rupture behavior

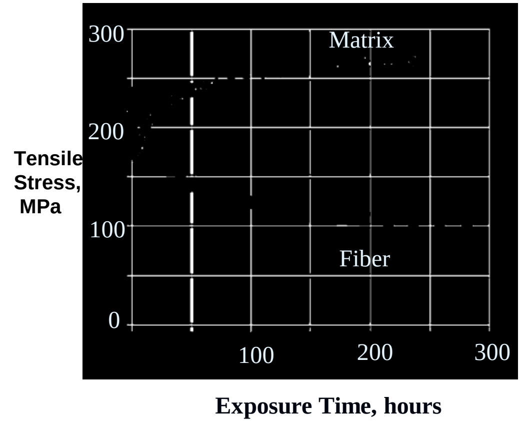




Improve fiber processing to obtain uniform microstructure & optimal properties

Constituent Creep Rates for SiC/SiC Composites

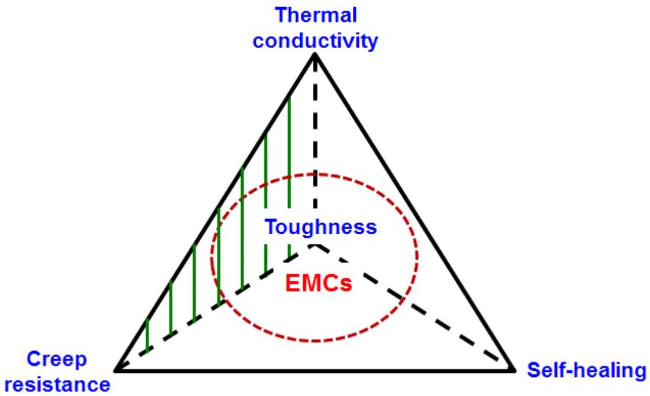


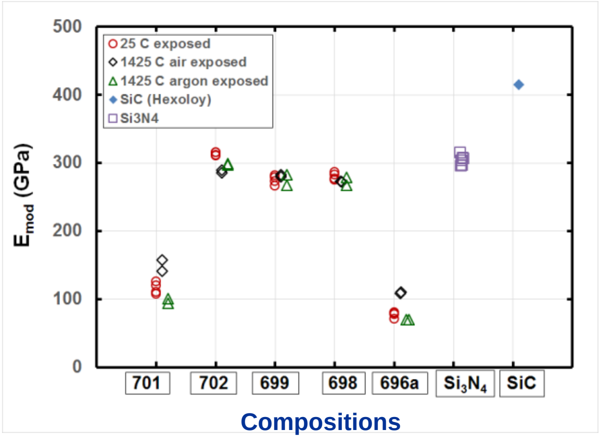


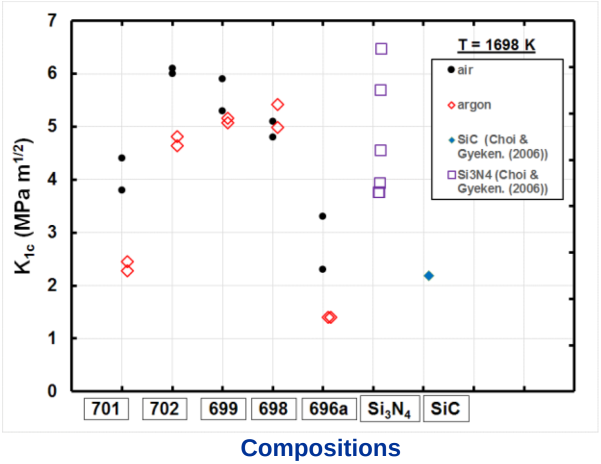
Fiber / Matrix Load Sharing
During Creep Deformation

- Above 2400⁰F, creep resistance of the SiC fibers is lower than that of the hybrid (CVI+PIP) SiC matrix, so long term durability of the CMC is controlled by matrix creep resistance
- To achieve 1000-hour CMC durability at 2700⁰F, an advanced SiC fiber should have a creep rate equal to that of the hybrid matrix
- 1000-hour durability requires a CMC creep rate < 10^{-9}/sec, and total creep < 0.4%.

Advanced Matrix Compositions Characterized



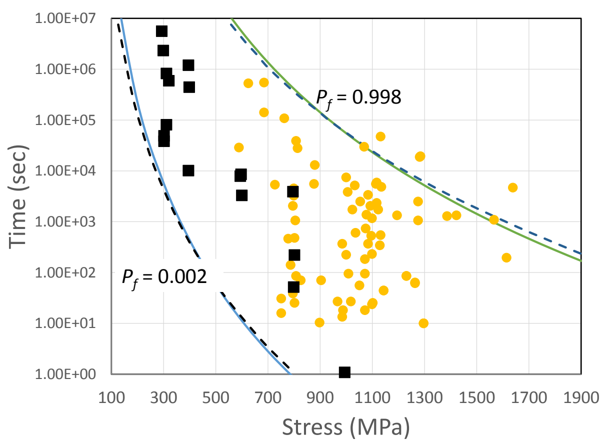




- Advanced CrMoSiGe/SiC/Si_3N_4 matrices with different self- healing additives have been investigated.
  - Self-healing additives have resulted in improved K_{1C} values.
  - High temperature fracture toughness 3X greater than monolithic SiC.
  - Room temperature elastic moduli equal to monolithic Si_3N_4.

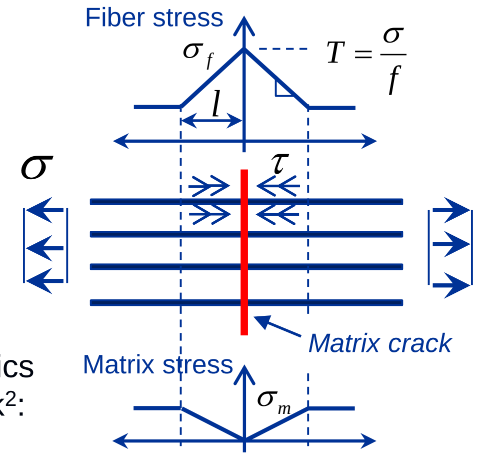
CMC / EBC Durability Modeling & Validation

Time-Dependent Stress Rupture Strength Degradation in SiC / SiC Composites

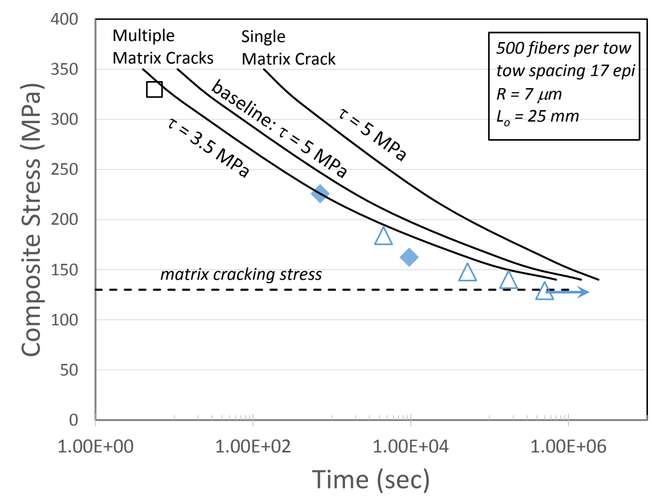


Time-to-failure vs applied stress for Hi-Nicalon fibers[1]

Force equilibrium mechanics at a matrix crack[2]:



***Conclusion:** Slow crack growth in fibers is the most significant time-dependent strength loss mechanism in Hi-Nicalon reinforced composites at intermediate temperatures.*



Fiber slow crack growth model explains stress versus time-to-failure data in Hi-Nicalon SiC/SiC composites [2]

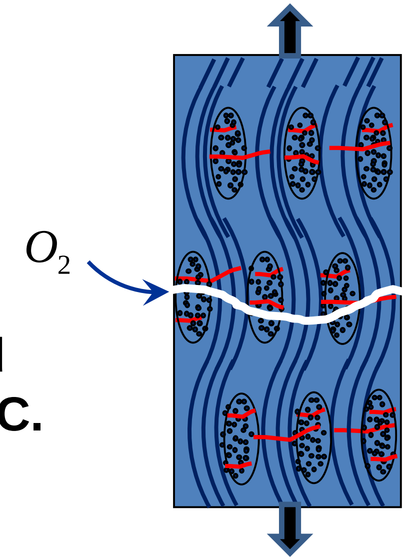
Contact: Roy.M.Sullivan@NASA.gov

[1] Gauthier and Lamon, *J. Amer. Ceram. Soc*., **92** [3] 702-709 (2009).

[2] Sullivan Roy M., NASA TM-2015-218939.

BN interface oxidation in SiC/SiC composites
model development & validation

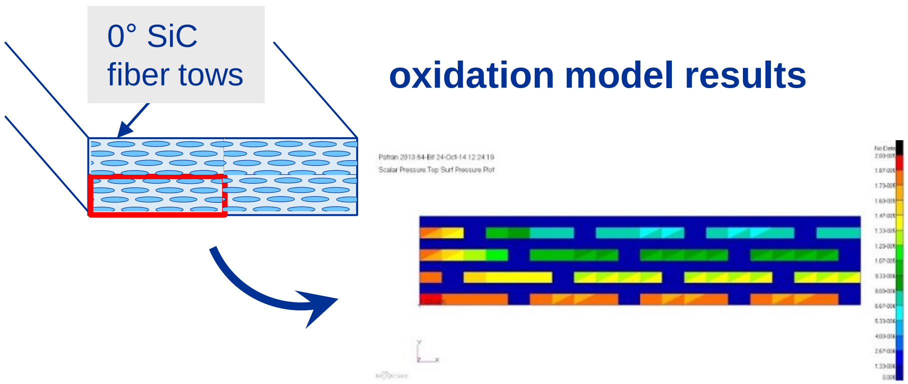
Objective: Determine interface oxidation mechanisms and model the mechanical-oxidation-creep interactions that affect the strength and life of SiC/SiC CMCs.



<u>Approach:</u> Perform parallel and correlative *experimental* and *numerical analysis* studies. Currently utilizing MI SiC/SiC CMC.

<u>Key Tasks</u>

- **Develop diffusion/oxidation model.**
- **Perform tests for model inputs.**
- **Perform stress rupture tests in oxidizing environment and characterize oxidation patterns on fracture surfaces.**
- **Develop failure model that incorporates effects of oxidation.**
- **Predict time to failure in various environments and applied loads.**



Oxidation patterns in crack plane: 1 atm air @ 1000 °C for 29 hours, 115 MPa applied stress

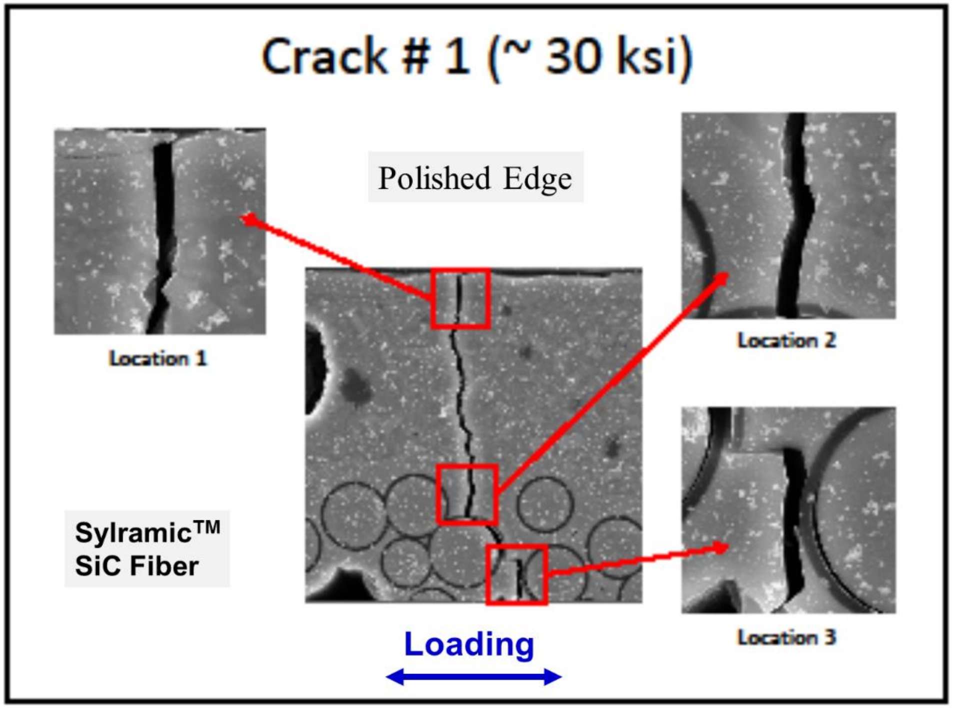
SiC/SiC Crack Opening Measurements

OBJECTIVE

- Crack opening displacements were needed to support GRC modeling of the oxidation of SiC/SiC CMCs at "intermediate" temperatures (815ºC).
- University of Michigan researchers used a small tensile loading fixture in an SEM to measure crack opening in a melt infiltrated SiC/SiC composite

RESULTS

- SEM provided the ability to observe and image cracks on the polished edge of the sample at high magnification.
- Following precracking at 25 ksi, images were captured at stress levels of 10, 15, 20, 25, and 30 ksi.

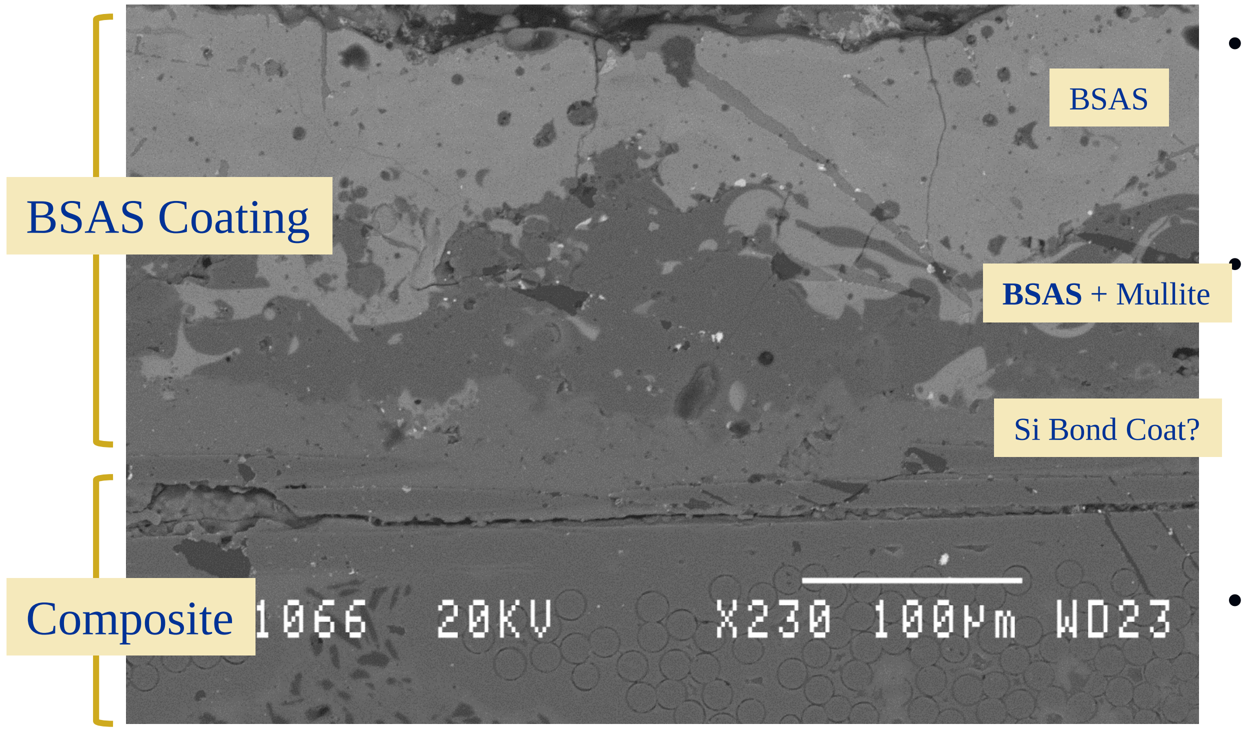


Measurements made in several locations along the crack

MichiganEngineering

Damage Progression in CMC/EBC Characterized

Tensile Surface



BSAS coated CVI/SMI SiC/SiC at ~8.5 MPa

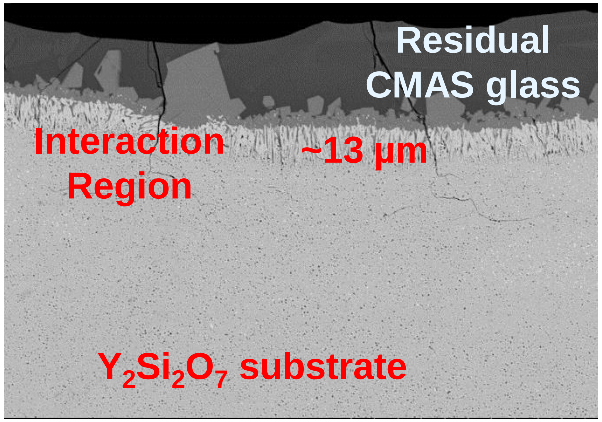
- **4-Point bend fixture was designed for use in SEM**
- **Loads applied incrementally to characterize damage progression**
- **EBC damage initiated in BSAS layer at 25% of first matrix cracking stress**

Contact: Martha.H.Jaskowiak@nasa.gov

CMAS interactions with EBC materials characterized

Characterization of thermal and mechanical properties of CMAS glass provides fundamental knowledge that will help to mitigate damage and improve EBC durability

Aircraft engine ingests sand on runway



$Y_2Si_2O_7$ substrate exposed to CMAS at 1200°C for 20h

Approach: evaluate interactions between heat treated EBC substrates with CMAS glass pellets

- Candidate EBC materials evaluated include:
  - Yttrium disilicate ($Y_2Si_2O_7$)
  - Hafnium silicate ($HfSiO_4$)
  - Ytterbium disilicate ($Yb_2Si_2O_7$)

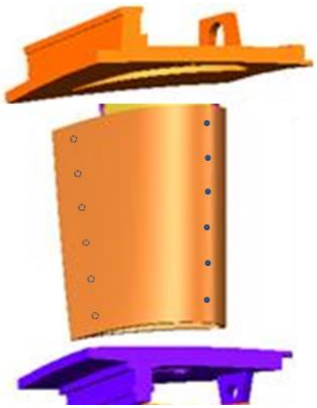
Progress in 2015:

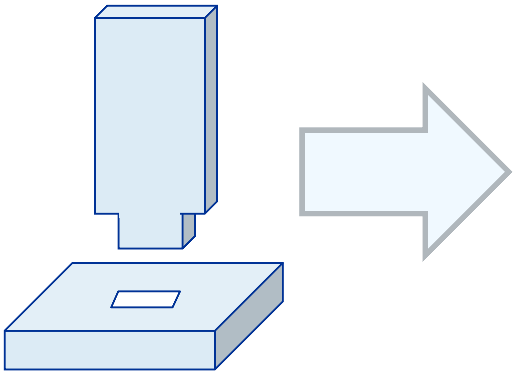
- High-temperature tests showed SOA models overestimate CMAS viscosity
- $Y_2Si_2O_7$ EBC exposed to CMAS glass formed apatite ($Ca_2Y_8(SiO_4)_6O_2$) phase

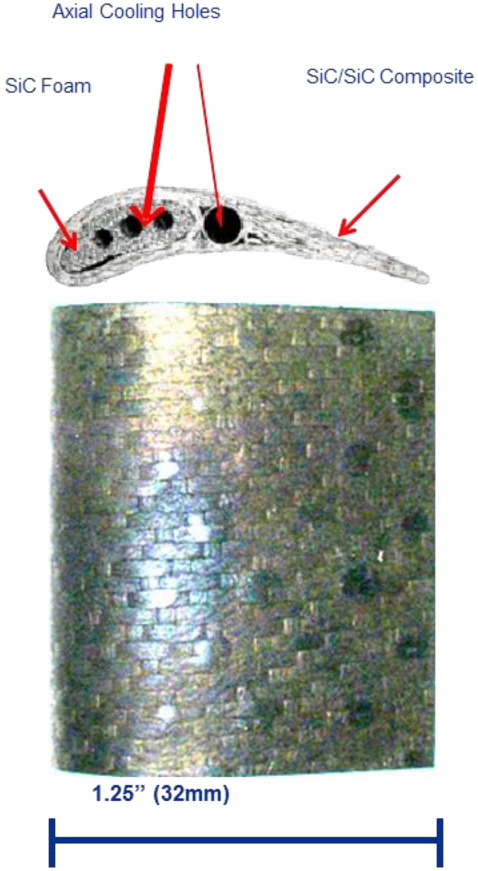
Contact: Valerie.L.Wiesner@nasa.gov

Advanced Manufacturing Technologies for CMCs

Evaluation of Advanced Joining Technology for a Turbine Vane Sub-element is in progress

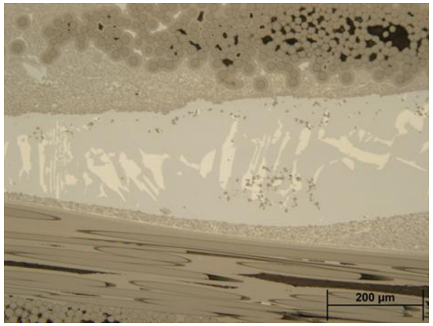


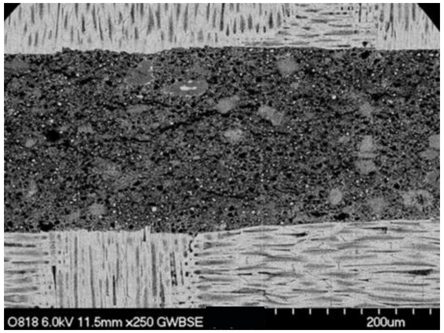




Easier fabrication compared to a continuous 3-D CMC vane.

Utilize NASA GRC Pressureless Joining Methods.

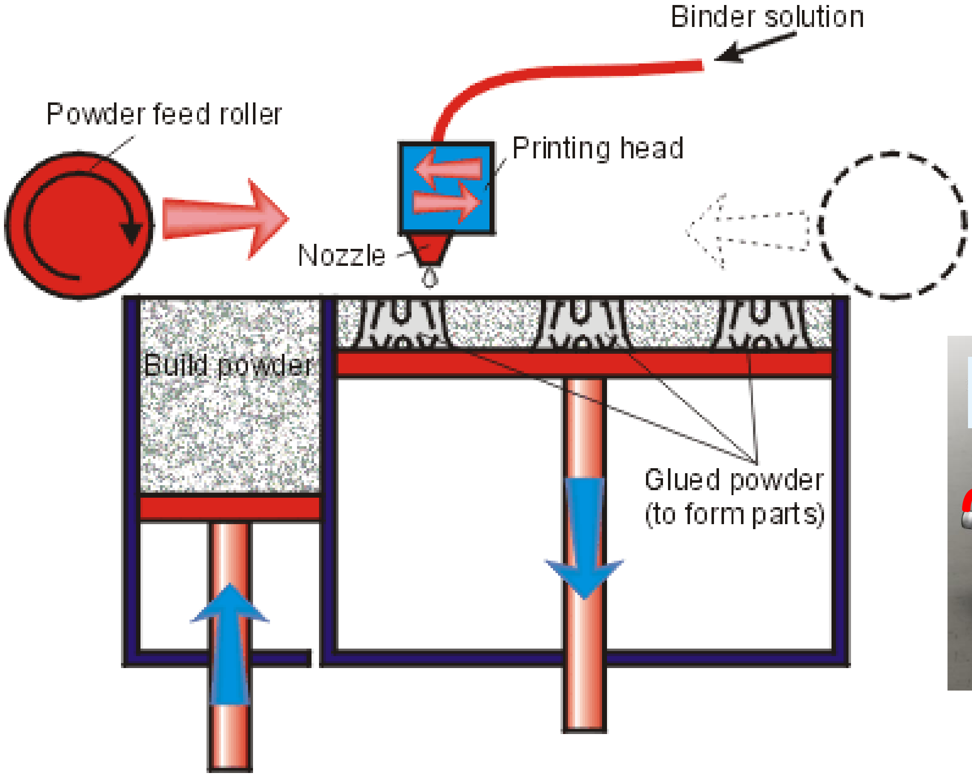


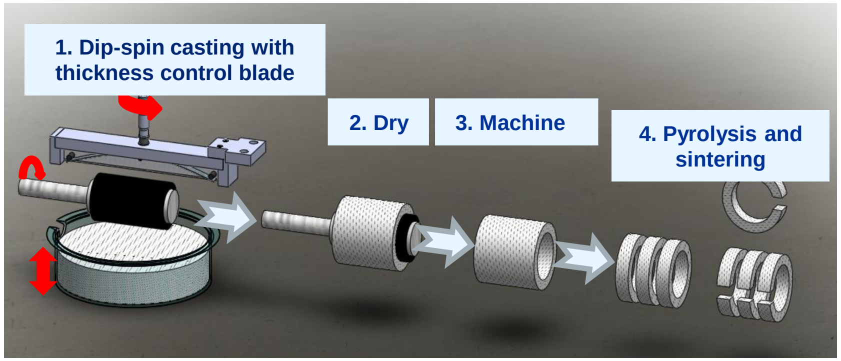


CMC to CMC using REABond and SET Joining.

Contact: Michael.C.Halbig@nasa.gov

Advanced Manufacturing Processes were adapted for fabricating Ceramic Matrix Composites





Binder Jet process

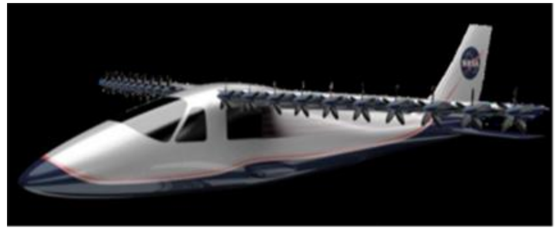
An inkjet-like printing head moves across a bed of ceramic powder, depositing a liquid binding material in the shape of the object's cross section

Horizontal Dip-Spin Casting

Enables fabrication of near-net shape ceramics with chopped fiber reinforcement for increased toughness and durability

Additive Manufacturing for Electric Motor Applications

NScrypt AM Machine
direct print micro-dispensing system



Electric Aircraft

Axial motor with a printed circuit stator

Size comparison: radial and axial flux motors

- Ability to co-print four separate materials on curved surfaces or build 3D structures.
- Accurate motion control and micro-dispensing volume control to 100 picoliters.
- Ability to print a wide variety of ceramic pastes (structural and functional), electronic pastes, adhesives, solders, bio-materials.

- Greener technology than turbine engines:
  - Reduced CO_2 emissions: batteries charged from environmentally friendly sources
  - Extremely quiet operation
- High power density electric motors allow for:
  - Larger pay loads and longer ranges.
  - Reduced weight and volume.

Initial focus is on axial flux motors with printed circuit stators

NASA GRC Focus in 2016

CMC Development & Characterization

- Characterize mechanical properties and durability of “Generation 2” Hybrid-matrix CMC for 2700°F applications
- Optimize NASA “in-situ BN” fiber heat treatment process for improved creep resistance
- Evaluate durability of 2700°F CMC / EBC system in component rig tests

CMC / EBC Durability Modeling & Validation

- Measure moisture effects on durability and failure modes of CMC/EBC system
- Fabricate and test subelement configurations using 2400°F + joining techniques

Additive Manufacturing

- Optimize AM processes for improved density, mechanical properties and durability of chopped-fiber CMC’s